Nonconventional Technologies Review
Romania, June, 2025

INFLUENCE OF LASER WELDING PARAMETERS ON THE CHARACTERISTICS OF JOINTS BETWEEN S355 CARBON STEEL AND 304 STAINLESS STEEL

Alina Bianca Pop [1], Gheorghe Ioan Pop [2], Aurel Mihail Ţîţu [3]and Sandor Ravai-Nagy [4,5]
[1] Technical University of Cluj-Napoca, North University Center of Baia Mare, 62A, Victor Babeș Street, Baia Mare, Romania, e-mail: bianca.bontiu@gmail.com
[2] S.C. Universal Alloy Corporation Europe S.R.L., Dumbravița 244A, 437145 Maramures, Romania, popghitza@gmail.com
[3] Lucian Blaga University of Sibiu, 10, Victoriei Street, Sibiu, România, e-mail: mihail.titu@ulbsibiu.ro
[4] Technical University of Cluj-Napoca, Faculty of Engineering, V. Babes Str. 62A, 430083 Baia Mare, Romania, sandor.ravai@imtech.utcluj.ro
[5] University of Nyíregyháza, Institute of Technical and Agricultural Sciences, Sóstói Str. 31/b, 4400 Nyíregyháza, Hungary, nagy.sandor@nye.hu

ABSTRACT: Joining carbon steel S355 with stainless steel 304 is a common challenge in industrial equipment manufacturing, and laser welding presents itself as a modern technological solution with high potential. This unconventional technique offers significant advantages in terms of precision, speed, and process control. Our study aims to assess the feasibility of laser welding for these materials, focusing on determining the optimal process parameters. We analyzed how different parameters - such as laser power, pulse frequency, wire feed speed, and laser beam travel speed - affect the shape and depth of the weld bead. The experiments conducted demonstrated that variables such as laser pulse frequency, wire feed speed, and wire diameter play a crucial role in weld quality. We observed, for instance, that an excessive wire feed speed can lead to porosity in the weld seam. By identifying the optimal welding configuration, our work contributes to the development of efficient and reliable methods for joining these two types of steel, offering a high-performance alternative to conventional techniques.

KEYWORDS: Laser welding, Carbon steel S355, Stainless steel 304, Welding parameters, Weld quality, Porosity

1. INTRODUCTION

Laser welding has become an indispensable technique in numerous industrial sectors, from automotive to electronics, due to its ability to produce high-precision joints with a small heat-affected zone and a higher processing speed compared to traditional methods [1,2].

This technology allows for the achievement of superior weld quality, with minimal distortion and improved aesthetics, making it ideal for applications requiring high accuracy [3,4].

A field of application with considerable potential is the joining of carbon steel S355 with stainless steel 304 [5,6]. This material combination is frequently used in the construction of industrial equipment, where mechanical strength and corrosion resistance are essential [7,8]. However, the significant differences between the physical and chemical properties of the two materials make their welding a technological challenge [9,10].

Currently, the joining of S355 with stainless steel 304 is mainly achieved through conventional methods, such as gas metal arc welding (GMAW). Although these methods are relatively well established, they present certain limitations regarding precise process control and joint quality, especially for parts with small thicknesses or complex geometries [11,12].

Our study focuses on exploring the potential of laser welding as an alternative to traditional techniques for joining S355 with stainless steel 304. We have identified several gaps in the specialized literature regarding this specific application, particularly concerning the optimization of welding parameters to achieve high-quality joints and minimize defects, such as porosity [13-15].

The novelty of this research lies in the systematic approach to investigating the influence of laser welding parameters (laser power, pulse frequency, travel speed, etc.) on the characteristics of S355 - stainless steel 304 joints. Through a detailed experimental study, we aim to identify the correlations between these parameters and weld quality, thus contributing to a better understanding of the process and its optimization for industrial applications.

The main objectives of this study are:

- To determine the optimal laser welding parameters for joining S355 carbon steel with 304 stainless steels.

- To evaluate the influence of these parameters on the geometry and microstructure of the weld bead.
- To analyze weld defects (porosity, cracks) and identify ways to minimize them.

This paper is structured in the following sections: Introduction, Materials and Methods, Results and Discussion, Conclusions, and References. The Materials and Methods section presents the materials used in the study and the experimental methodology. The Results and Discussion section analyses the experimental data obtained and discusses the influence of welding parameters on weld quality. Finally, the Conclusions section summarizes the main findings of the study and provides recommendations for practical applications.

2. MATERIALS AND METHODS

In this experimental study, two base materials were used: St52 carbon steel and 304 stainless steels. The choice of these materials was motivated by their frequent use in the machinery and equipment manufacturing industry, where joining them by welding is often required.

St52 carbon steel, also known as S355 according to the European standard EN 10025, is a general-purpose steel with good mechanical strength and weldability. Its chemical composition, as specified in the standard, is presented in Table 1.

Table 1. Chemical composition of S355 steel

Element	C (%)	Si (%)	Mn (%)	P (%)	S (%)
Maximum admissible content	0.22	0.55	1.6	0.035	0.035

Stainless steel 304 (1.4301 according to EN 10088) is an austenitic steel with a high chromium and nickel content, which gives it excellent corrosion resistance. Its chemical composition is shown in Table 2.

Table 2. Chemical composition of 304 stainless steel

Element	C (%)	Si (%)	Mn (%)	Cr (%)	Ni (%)
Maximum admissible content	0.03	1	2	17.5-10.5	8-10.5

To ensure optimal weldability and enhance the mechanical properties of the joint, filler material in the form of wire with diameters of 1 mm and 1.2 mm was used.

Two types of filler material were employed, each with different chemical compositions, tailored to the specific base materials and welding parameters.

Table 3. Filler metals used

No.	Filler metals	Diameter (mm)	Chemical composition (%)
1	309 RSi	1	C 0,02%, Si 0,85%, Mn 1,75%, Cr 19,0%, Ni 9,5%-
2	308 L	1.2	C max: 0.08 %; Mn max;2.0 % Si max 0.75%; P max 0.045%; S max 0.03%; Cr min: 22.0 max: 24.0%; Ni min: 12.0 max: 15.0%

The experiment was conducted using a Xweld VVL2000 laser welding equipped with a fiber laser source with a maximum power of 2 kW. The shielding gas used was high-purity argon (99.99%), with a constant flow rate of 10 l/min, to prevent oxidation and contamination of the weld pool.

Investigating the influence of welding parameters on joint quality was a central aspect of this study. The main parameters that were varied during the experiments are presented in Table 4.

Table 4. Welding parameters used in the experiments

Parameter	Unit of measurement	Range of variation
Laser source power	kW	1.5 - 2.0
Pulse frequency	Hz	1000 - 2000
Wire feed speed	cm/min	130 - 240
Beam weaving	mm	5
Gap distance	mm	1.5

The selection of these parameters and their ranges of variation was based on the recommendations of the welding equipment manufacturer and on preliminary data obtained in previous tests. A total of 9 weld beads were produced, each with a unique combination of parameters, to cover a wide spectrum of welding conditions. This approach allowed for a comprehensive analysis of the influence of each parameter on the characteristics of the welded joint.

3. RESULTS AND DISCUSSIONS

3.1 Analysis of the influence of welding parameters on weld bead quality

Investigating the influence of welding parameters on joint quality was a central objective of this experimental study. Analysis of the results revealed a strong correlation between the welding parameters (laser source power, pulse frequency, wire feed speed) and the characteristics of the weld bead, particularly its geometry and the presence of any defects.

Laser source power had a direct impact on the penetration depth and width of the weld bead. An increase in laser power resulted in a greater penetration depth and a narrower bead width, indicating a higher concentration of energy. This effect is illustrated in Figure 1 and Figure 2, where a clear difference can be observed between the geometry of the beads produced with different laser power levels.

Pulse frequency mainly influenced the surface roughness of the weld bead. A higher pulse frequency showed a trend of reducing roughness and improving the surface appearance. This aspect is visible in Figure 3 and Figure 4, where the beads produced with a higher pulse frequency exhibit a smoother surface.

Wire feed speed had a significant impact on the bead geometry and the occurrence of porosity. High wire feed speeds led to a smaller bead width and a tendency for pore formation within the bead structure. This phenomenon is illustrated in Figure 5 and Figure 6, where the presence of porosity can be observed in the beads produced with high wire feed speeds. This issue can be attributed to excessively rapid cooling of the weld pool, which hinders the escape of dissolved gases from the molten metal.

For a more detailed analysis, each case is presented individually below.

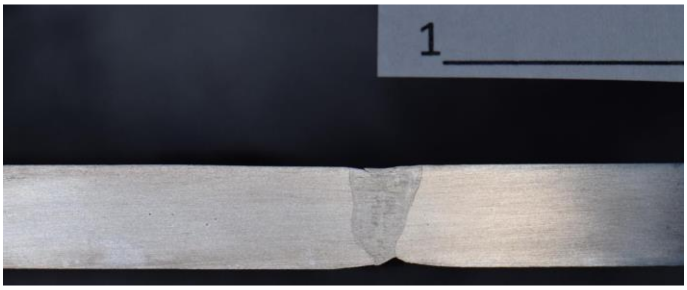

Figure 1. Weld bead 1

Figure 1 shows a weld bead produced with a laser power of 1.5 kW, a pulse frequency of 1000 Hz, and a wire feed speed of 130 cm/min. A moderate penetration depth and a relatively wide bead width can be observed.

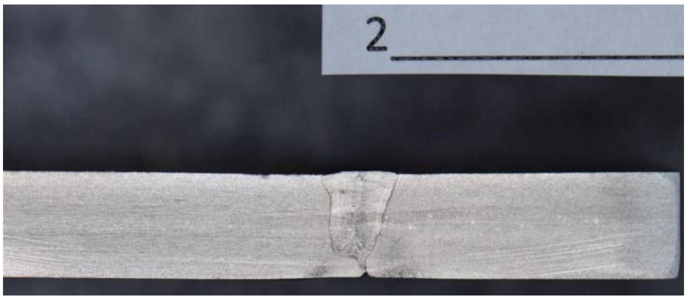

Figure 2. Weld bead 2

Figure 2 shows the weld bead produced with a laser power of 2.0 kW, a pulse frequency of 1000 Hz, and a wire feed speed of 130 cm/min. The penetration depth is greater, and the bead width is comparable to that shown in Figure 1.

Figure 3. Weld bead 3

Figure 3 shows the weld bead produced with a laser power of 1.5 kW, a pulse frequency of 2000 Hz, and a wire feed speed of 130 cm/min. The surface of the bead is more concave than that in Figure 1.

Figure 4. Weld bead 4

Figure 4 shows the weld bead produced with a laser power of 2.0 kW, a pulse frequency of 2000 Hz, and a wire feed speed of 130 cm/min. A high penetration depth and a concave surface and the appearance of the first pores

Figure 5. Weld bead 5

Figure 5 shows the weld bead produced with a laser power of 1.5 kW, a pulse frequency of 1000 Hz, and a wire feed speed of 240 cm/min. The bead width and deep is reduced, and pores are present within its structure.

Figure 6. Weld bead 6

Figure 6 shows a weld bead produced with a laser power of 2.0 kW, a pulse frequency of 1000 Hz, and a wire feed speed of 240 cm/min. In this case, the weld bead section is smaller than in Figures 1 - 4.

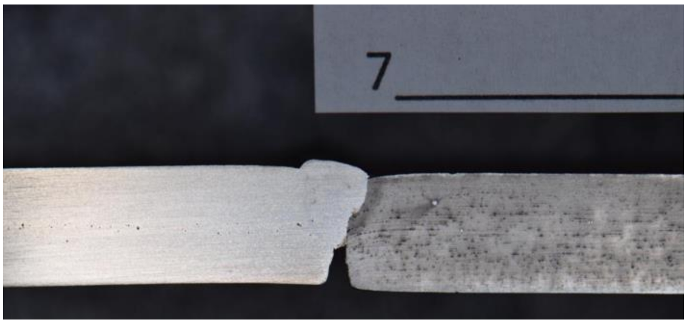

Figure 7. Weld bead 7

Figure 7 shows a weld bead produced with a laser power of 1.5 kW, a pulse frequency of 2000 Hz, and a wire feed speed of 240 cm/min. A slight increase in the penetration depth is observed compared to Figure 6, due to the higher frequency of pulses.

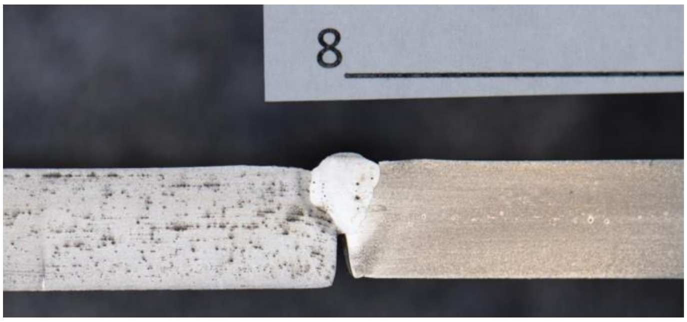

Figure 8. Weld bead 8

Figure 8 shows the weld bead produced with a laser power of 2.0 kW, a pulse frequency of 2000 Hz, and a wire feed speed of 240 cm/min. The weld bead is porous, and the penetration depth is around 50% of the thickness of the welded sheets.

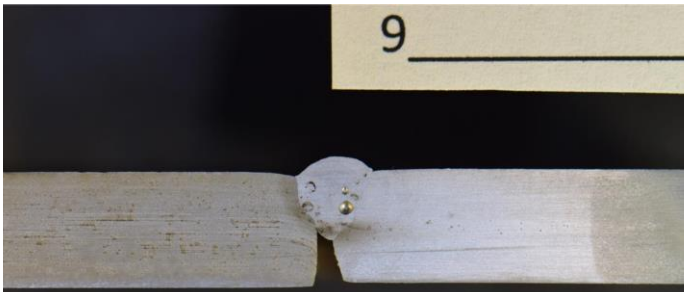

Figure 9. Weld bead 9

Finally, Figure 9 shows a cross-section of a weld bead (parameters: laser power 2.0 kW, pulse frequency 2000 Hz, wire feed speed 130 cm/min). The weld bead has large pores and a penetration depth of around 50% of the thickness of the welded sheets.

3.2 Discussion of the Correlation between Welding Parameters and Joint Characteristics

The experimental results confirm that laser welding of S355 carbon steel with 304 stainless steel is a complex process, influenced by a multitude of factors. Identifying the correlations between welding parameters and joint characteristics is essential for process optimization and achieving high-quality welds.

The study demonstrated that laser power plays a key role in determining penetration depth, while pulse frequency primarily affects the surface roughness of the weld bead. Wire feed speed is a critical parameter, as it influences both the bead geometry and the tendency for porosity formation.

It is important to note that these parameters do not act independently, but rather in an interdependent manner. For example, an increase in wire feed speed can be compensated for by increasing the laser power to maintain adequate penetration depth. Therefore, optimizing the welding process requires a holistic approach that considers the interaction among all involved parameters.

Further investigation of the microstructure of the welded joints using optical and electron microscopy techniques would be beneficial to this study. This would allow for a more precise assessment of joint quality and a better correlation between welding parameters and the mechanical properties of the welds. Additionally, investigating the influence of other parameters, such as shielding gas type and flow rate, laser focal length, and beam angle of incidence, would be useful.

Another important aspect worth investigating in the future is the influence of post-weld heat treatment on joint properties. Applying an appropriate heat treatment can contribute to reducing residual stresses and improving the mechanical characteristics of the weld.

In addition to the aforementioned aspects, it would be interesting to evaluate the performance of the welded joints under real operating conditions by testing their corrosion resistance, fatigue strength, and other application-specific requirements.

In conclusion, laser welding proves to be a promising technology for joining S355 carbon steel with 304 stainless steel, offering a series of advantages in terms of precision, speed, and process control. However, process optimization requires a thorough understanding of the influence of welding parameters and an integrated approach that considers the complex interaction between them.

4. CONLUSIONS

The conducted experimental study allowed for a detailed analysis of laser welding of S355 carbon steel with 304 stainless steel, highlighting the potential of this unconventional technology, as well as the associated challenges.

The main conclusions drawn from this research are:

- The significant influence of welding parameters (laser power, pulse frequency, wire feed speed) on welding bead characteristics was confirmed. Laser power primarily determines penetration depth, pulse frequency affects surface roughness, and wire feed speed influences bead geometry and the occurrence of porosity.
- High wire feed speeds can induce porosity in the weld bead, most likely due to rapid cooling and the inability of gases to escape from the weld pool.
- Achieving high-quality joints requires careful selection of welding parameters, considering their interdependence.

Recommendations for practical applications:

- Avoiding excessive wire feed speeds is recommended to prevent the occurrence of porosity.
- Continuous monitoring of welding parameters is essential to ensure consistent joint quality.
- Further studies are needed to investigate the influence of other parameters (such as shielding gas type or laser beam focus) and to further optimize the welding process.

This research contributes to a better understanding of laser welding of S355 carbon steel with 304 stainless steel.

The results obtained can be used to optimize the welding process in industrial applications, leading to improved joint quality and reliability.

Through its experimental approach and systematic analysis of welding parameters, this study provides valuable information for the development and implementation of laser welding technology in the manufacturing industry.

5. REFERENCES

1. Arulvel, S., Jain, A., Kandasamy, J. and Singhal, M., Laser processing techniques for surface property enhancement: Focus on material advancement. *Surfaces and Interfaces*, *42*, p.103293, (2023).
2. Shin, Y.C., Wu, B., Lei, S., Cheng, G.J. and Lawrence Yao, Y., Overview of laser applications in manufacturing and materials processing in recent years. *Journal of Manufacturing Science and Engineering*, *142*(11), p.110818, (2020).
3. Gonçalves, L.F., Duarte, F.M., Martins, C.I. and Paiva, M.C., Laser welding of thermoplastics: An overview on lasers, materials, processes and quality. *Infrared Physics & Technology*, *119*, p.103931, (2021).
4. Andersson, J., Welding metallurgy and weldability of superalloys. *Metals*, *10*(1), p.143, (2020).
5. de Albuquerque Vicente, A., D'silva, P.A., de Souza, R.L., dos Santos, I.L., de Aguiar, R.R. and Junior, A.B.B., The use of duplex stainless steel filler metals to avoid hot cracking in GTAW welding of austenitic stainless steel AISI 316L. *International Journal of Advanced Engineering Research and Science*, *7*, pp.345-355, (2020).
6. Ferro, P. and Nilsson, J.O., Welding metallurgy of stainless steels. In *Handbook of Welding: Processes, Control and Simulation* (pp. 1-39). Nova Science Publishers, Inc., (2021).
7. Webb, C. and Jones, J.D. eds., *Handbook of Laser Technology and Applications: Volume 3: Applications*. CRC Press, (2020).
8. Wang, J., Fang, F., An, H., Wu, S., Qi, H., Cai, Y. and Guo, G., Laser machining fundamentals: micro, nano, atomic and close-to-atomic scales. *International Journal of Extreme Manufacturing*, *5*(1), p.012005, (2023).
9. Farshidianfar, A., Nabavi, S.F. and Farshidianfar, M.H., *The Laser Manufacturing Process: Fundamentals of Process and Applications*. CRC Press, (2024).
10. Shugaev, M.V., He, M., Levy, Y., Mazzi, A., Miotello, A., Bulgakova, N.M. and Zhigilei, L.V., Laser-induced thermal processes: heat transfer, generation of stresses, melting and solidification, vaporization, and phase explosion. In *Handbook of Laser Micro-and Nano-Engineering* (pp. 83-163). Cham: Springer International Publishing, (2021).
11. Górka, J., Assessment of the effect of laser welding on the properties and structure of TMCP steel butt joints. *Materials*, *13*(6), p.1312, (2020).
12. Kuryntsev, S., A review: laser welding of dissimilar materials (Al/Fe, Al/Ti, Al/Cu)—methods and techniques, microstructure and properties. *Materials*, *15*(1), p.122, (2021).
13. Singh, R., *Applied welding engineering: processes, codes, and standards*. Butterworth-Heinemann, (2020).
14. Daggett, C., Daggett, A., McBurney, E. and Murina, A., Laser safety: the need for protocols. *Cutis*, *106*(2), pp.87-92, (2020).

Zuo, J. and Lin, X., High-power laser systems. *Laser & Photonics Reviews*, *16*(5), p.2100741, (2022).